PCSAT2: Synergy in the Amateur Satellite Service

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Abstract

PCSAT2 is a follow-on digital communications payload to the highly successful PCsat[1] that was launched on 30 Sept 2001. PCSAT2 evolved from our success with PCsat's off-the-shelf command, control and telemetry design and the Navy's availability of a solar cell experiment that was going to fly as an external payload on ISS this year. Due to the Navy's short fuse and with only 9 months development time available, the Navy payload was going to be a passive sample-return mission with no external communications capability. But since it was a solar experiment, the non solar facing half of the experiment box was available for an educational payload.

Combining the two missions lead to synergistic advantages for both parties and a resulting communications experiment that was perfect for operating within the rules of the Amateur Satellite Service[2].

The original PCsat was a complete success and it has been used by thousands of users in its first 19 months of flight. It has validated the viability of using off-the-shelf AX.25 for all Telemetry Command and Control as well as supporting a bent-pipe user communications mission. We have many lessons learned and experiences with spacecraft operations from PCsat and many ideas for the future. This paper summarizes the design and operations background from PCsat and then provides details for the PCSAT2 mission design.
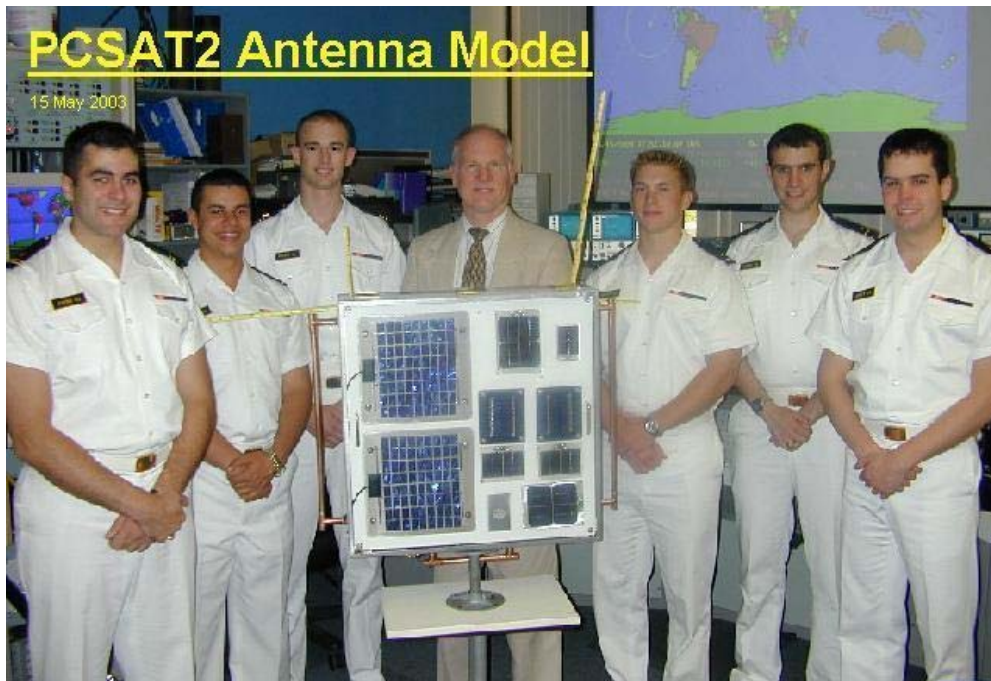
Photo 1. The PCSAT2 Design Team at the US Naval Academy

The PCSAT APRS Mission

The digital communications mission implemented in the original PCsat and our new PCSAT2 is a generic mission using the ubiquitous AX.25 protocol used in many of the satellites in the Amateur Satellite Service. The digital transponder provides real-time message, position, and status relay via satellite to a worldwide Internet linked amateur radio tracking system. Any amateur or university payload can support this mission by simply enabling the DIGIPEAT-ON function in any AX.25 compatible transponder (TNC). The users of such a relay system can be for Boats at Sea, remote environmental sensors[3], cross country travelers, expeditions, school projects, or any other users which are far from any existing APRS terrestrial digital network.

The AX.25 satellite downlink from this mission is fed into the existing worldwide Internet linked ground system by participating ground stations. Our ultimate objective is to have all such AX.25 satellites work together as a constellation of digital transponders to provide connectivity to everyone in the Amateur Satellite Service[4].

Photo 2. Prototype Communications Satellite (PCsat) with Antennas

The Space segment of PCsat/APRS had been demonstrated a number of times in space via MIR School tests[5,6], the Shuttle SAREX[7], the SPRE mission, AO-16, UO-22 and more recently via SUNSAT and ISS and PCsat. Full details of the PCsat mission can be found at:

http://www.ew.usna.edu/pcsat

http://www.ew.usna.edu/~bruninga/astars.html

PCsat Mission Accomplishments

Although PCsat was only designed for a one year mission, it continues to operate (now after 20 months) with no on-orbit failures except for the failed –Z solar panel on launch. This reduced power budget by over 20% and caused early weakening of the battery system due to deep cycling during long eclipses. Still, PCsat works well on every orbit while it is in the sun. During the first 19 months of operations, it logged over 2000 users all around the world and the worldwide amateur tracking network fed all data live to the http://pcsat.aprs.org web page so that it was available to everyone participating live.

Further PCsat communications were used in a number of high profile Amateur Satellite demonstrations and events. See the PCsat paper in last year's proceedings[8].

Also, PCsat carried a successful GPS system which conducted several acquisition and accuracy experiments[9].

The popularity of PCsat was evidenced by coverage on National Public Radio on 13 Nov, Online-Tonight and CNN on 27 Jan 2002. Stories were also widely published by the Associated Press, Air and Space magazines as well as all of the Amateur Satelliite literature giving great exposure to the Amateur Satellite Service and student developments.

Design Validation

The following elements of PCsat's design were validated and performed flawlessly:

- Dual Redundant payloads/systems
- Commands and Hardware redundancy
- Commercial Teflon coated solar panels
- Orbit temps within 10 deg variance
- Thermal design balanced within 5 deg
- Radiometer spin between .5 and 1 RPM
- Magnetic Stabilization
- Good link budgets
- Ground station Internet Linked system
- Fail-safe circuits and SEU recovery
- Discipline of User Service Agreement

The only failure was the –Z solar panel, which was actually anticipated as it had had two problems during manufacture but was flown anyway because we had no backup.

AX.25 Digital Communications Protocol

An advantage of the AX25 protocol is that any node in the system can be used for relaying data between any other nodes. Thus, the TNC can not only provide the dedicated up and downlinks and command/control channels, but also serve as a generic relay for other applications on a secondary basis. Examples of TNC's on orbit are SAREX, SPRE, MIR, ISS, SUNSAT, OPAL, PCsat, SAPPHIRE and STARSHINE-3. But PCsat was the first to use the TNC as the complete Spacecraft system controller with no other CPU's on board.

PCSAT2 HARDWARE REQUIREMENTS

The full design of PCSAT2 is on-line at www.ew.usna.edu/~bruninga/ pcsat2.html.

Since PCSAT2 was designed in our Aerospace Department and there were no participating students with experience in software or CPU design, the satellite control system was designed around two KPC-9612+ Dual Port TNC's. These TNC's have all the latest APRS generic digipeating advantages as well as telemetry, command and control and can even cross route packets between ports. By using standard off-the-shelf TNC hardware and FIRMWARE, on orbit risk was minimized due to the track record of thousands of identical hardware in use all across the country.

The dual baud rates of the dual port KPC-9612+ were used differently. The bulky solar experimental data was transmitted in short 1 second bursts at 9600 baud to minimize channel load while user communications took advantage of the 7 dB better link budget on the 1200 baud port.

Further, the availability of the dual receivers and transmitters allowed for other experimental communications modes to be supported such as PSK-31 multi-user narrowband transponder and a voice FM repeater as shown in Figure 3 and later in Figure 7.
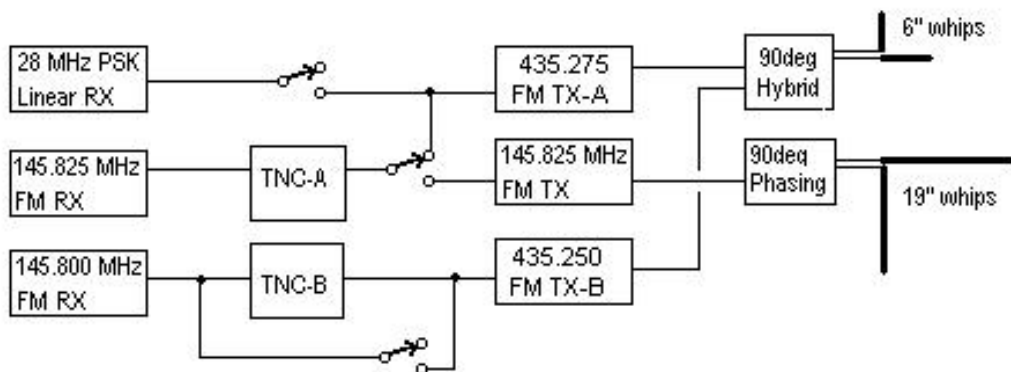

Figure 3. PCSAT2's dual AX.25 command and control system transponders can also be switched into modes to support PSK-31 and FM voice operation.

The PCsat 9600 Baud KPC-9612+

The Kantronics 9612+ TNC as used on PCsat and now designed into PCSAT2, has dual serial comm ports supporting both 1200 and 9.6 to 38.8 Kbaud. The 9612+ also offers 5 analog telemetry channels and a total of 8 configurable command or I/O bits, plus four ON/OFF command bits and one input bit. These features were sufficient to handle all of the Telemetry Command and Control for PCsat and PCSAT2 as detailed below.

PCSAT2 Design for Space Station

PCSAT2 is not a free-flying satellite, but an attached external payload for installation on the ISS by an Astronaut during an EVA. This presented many design challenges that are quite

different from a free-flyer in the areas of power, safety and thermal. The PCSAT2 comms
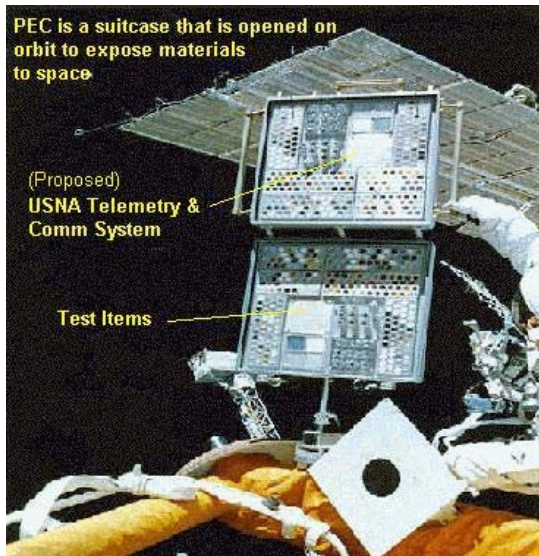

Figure 4. The PCSAT2 "suitcase".

payload is in the back half of a suitcase like box that is opened on orbit to expose the new technology solar cells to the space environment as shown in Figure 4.

Since the ISS is flown in a stable attitude, this means that the solar arrays on one side of PCSAT2 would only face the sun under unique orientations. Fortunately, the articulated solar array truss was to arrive on station prior to PCSAT2's arrival so we were offered an attachment point beyond the alpha

solar joint so that our panels would move with the station's arrays. Unfortunately, delays in the Shuttle program have now made our arrival after this solar array truss and current plans may attach us in a fixed orientation with much less average solar power available.

The preferred location for PCSAT2 is out on the ISS Solar array, beyond the alpha joint so that it gets full sun when ISS is in Sun. Our preferred location is shown with the arrow.

Figure 5. Ideal location of PC2.

PCSAT2 EVA Safety Issues

Since PCSAT2 will not only being flying on ISS, but is also installed by an astronaut during an EVA, the man safety requirements were significant. The 2 watt transmit power for the PCSAT2 communications systems exceed the
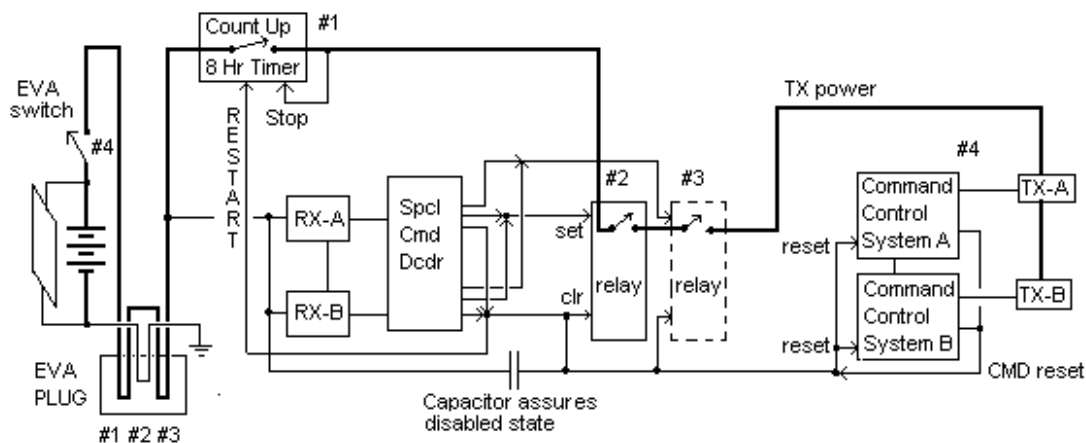

Figure 6. Transmit Inhibits required for Astronaut Safety during EVA.

safe limits for operation near an astronaut in an EVA suit and are considered a catastrophic hazard by NASA. To assure safety, one switch and 3 more redundant power-inhibit contacts were required while the PCSAT2 was in the payload bay and while being handled by an astronaut. Further, once PCSAT2 is installed by a crew member, there has to be four additional transmit inhibits to preven any inadvertent activation from the ground until the installing astronaut is clear of the device. This is accomplished via an additional 8 Hour timer and 3 more ground commandable inhibits.

PCSAT2 PSK-31 Multi-User Transponder:

PCSAT2 will be the first satellite to support a dedicated PSK-31 digital transponder[10]. PSK-31 is a digital Phase Shift Keying mode that is very successful with weak signals and is an ideal mode for students to learn about easy communications via satellite. PSK-31 is only 31 baud and because of its narrow bandwidth, up to 20 or more signals can share a single voice equivalent transponder channel.

Another significant advantage to PSK-31 is that the original author wrote the modem in software and made it public. Thus, only a PC with a sound card is needed for this very exotic communications technique. Figure 7 below shows the typical audio spectragram showing that there are 6 PSK-31 signals in the passband. Two of them are decoded in the text boxes shown and a seventh station has transmitted his callsign in what is called Hellinschreiber which is a quasi FAX technique in the same spectrum.

PSK-31 communications has not been practical through other satellites because of high Doppler. Being only 31 Hz wide, accurate decoding has to be with a Hz or so and with satellite downlinks experiencing as much as +/- 10 KHz during a typical pass, it is just not practical. But PCSAT2 solves the problem of Doppler by using an HF frequency for uplink which only has about +/- 600 Hz Doppler spread over the 10 minute pass, but then eliminates all linear downlink Doppler by sending down the entire passband as a single FM audio channel. As long as the FM signal stays within the passband of the receiver, the signals are received without Doppler. Thus, everyone sees the same audio spectrogram and the only source of Doppler is each stations own uplink Doppler for which he can easily compensate.
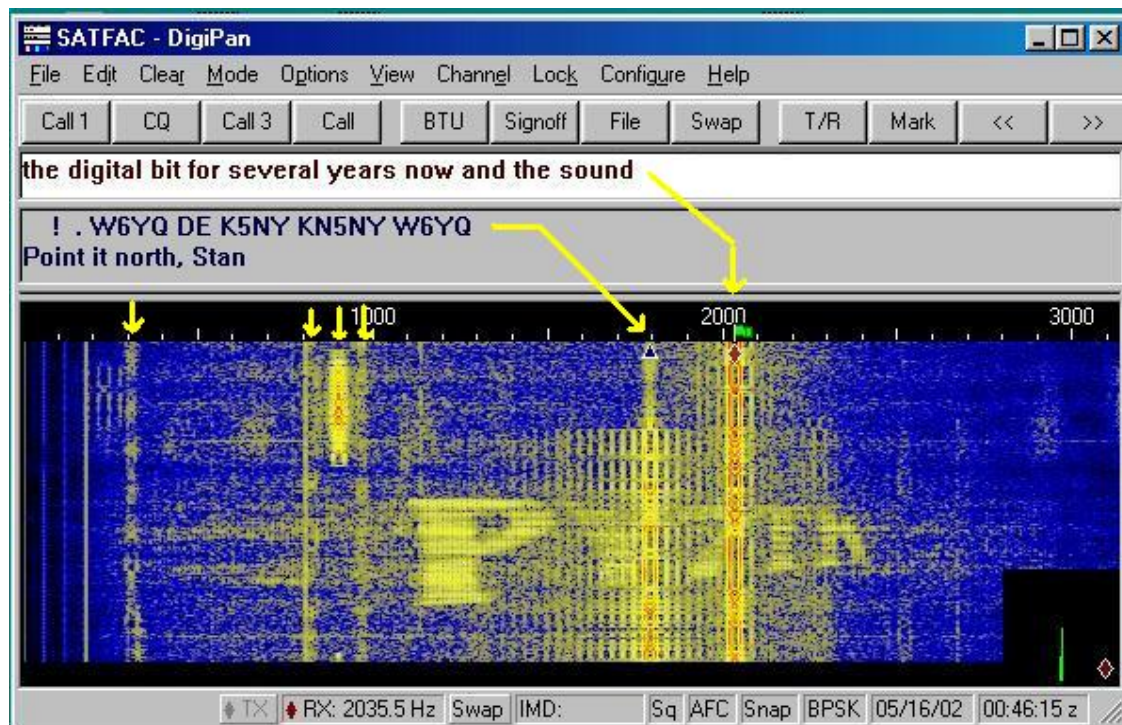

Figure 7. The PSK-31 audio spectragram showing 7 user signals.

PCSAT / ASTARS BACKGROUND

ASTARS (for APRS Satellite Tracking and Reporting System) is the space segment of the APRS system which has evolved through a number of existing and previous satellite experiments. First was **1200 Baud PSK ASTARS (**called TRAKNET [11] at the 1998/99 AMSAT conferences) using AO-16, LO-19 and IO-26. But these required specialized modems.

Satellite packet experiments using **1200 Baud AFSK ASTARS,** however, which *any* TNC can do, were demonstrated many times during experiments with the Space Station MIR[6] packet system and SAREX[7]. A week long experiment via MIR which used the new Kenwood TH-D7 During this test[5], over 55 stations conducted 2 way hand-held message communications.

In the year 2000, experiments were conducted with **9600 BAUD ASTARS** using UO-22 and SUNSAT and the new Kenwood 1200/9600 baud APRS data mobile radio, the TM-D700A shown below.

Photo 8. Chas Richard, W4HFZ's mobile APRS
Satellite capability (including HF.

PCSAT and the INTERNET

Unlike previous Amateur Satellite design, PCsat capitalized on the connectivity of the Internet by linking together multiple disparate downlink sites to provide a tremendous gain in reliability through space and time diversity reception. Instead of each station requiring their own downlink receiver and then only being able to hear packets within his own footprint, the Internet allows a few stations, called SAT-Gates (Satellite IGATES) to combine all packets heard into the existing worldwide APRS infrastructure (TELNET to second.aprs.net) for delivery to any APRS operator anywhere.
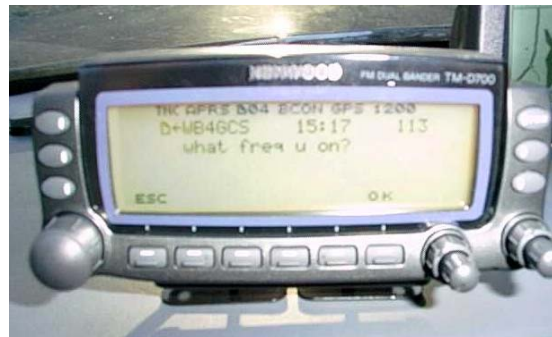

Photo 9. The front panel of the TM-D700 showing an incoming 15 byte message (Messages can be up to 64 bytes).

FAILSAFE RESET

To recover from a SEU or other lockup condition in these commercial off-the-shelf TNCs, PCSAT2 uses 3 methods of hardware resets back to launch defaults. First, there is a 96 hour hardware reset timer that will reset the TNC's if it has not been contacted at least once every 3 days. Second, a hardware command via one TNC can reset the other. Third, a backup command system has a backdoor reset capability for each TNC.

TELEMETRY

PCSAT2 uses the APRS 5 channel TELEMETRY format published for the MIM module in 1995 that Kantronics subsequently added to their "plus" family of TNC's. To make this usable on PCSAT2, we added a 20-to-5 hardware multiplexer to allow telemetry to read as many as 20 analog values and 5 status bits transmitted in four consecutive telemetry packets. For others contemplating similar AX.25 satellite systems, photos of the MIM module and KPC-3+ are shown below.

The MIM Module

The simplest Telemetry module is the one cubic inch MIM module which provides for multiple periodic AX.25 packets at 1200 baud AFSK with up to 5 analog channels and 8 on/off bits. Different rates can be set for the BEACON,

Telemetry, GPS position and CW ID's. The module has no command and control capability, but that is easily added with CTCSS or DTMF decoders. The MIM module, developed at the Naval Academy, is now available from Stanford University Small Satellite Program.

Photo 10. The MIM module designed by the author and now in production at Stanford Univ.

1200 Baud KPC-3+

The second and more capable telemetry is the use of a Kantronics KPC-3+ TNC which has the advantage of an AX.25 data receiver and thus the ability to do command and control. It can even be carved down to fit within a four inch cubesat. The KPC-3 is being used as the comm. Payload on the ANDE mission [12].
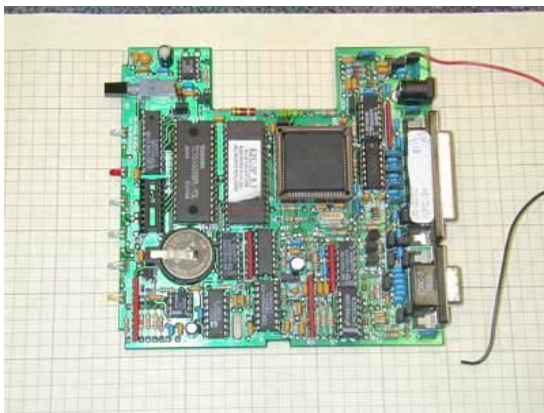

Photo 11. The KPC-3+ TNC system.

This gives the same Telemetry, Beacon, GPS and CW ID capability as with the MIM module, but includes a full TNC DIGIPEATER and 4 channel COMMAND/CONTROL channel as well.

LINK BUDGET

The primary driver of this APRS Satellite design was to deliver messages to handhelds and mobiles with only whip antennas. For this, the downlink needed to be at least 12 dB stronger than most existing digital satellites. PCSAT2 accomplishes this by taking advantage of the 9 dB link improvement of 2 meters compared to 70 cm and by using a 2 watt transmitter. Unfortunately, 2 meters may often conflict with other Amateur Radio Experiments (ARISS) on the ISS, so PCSAT2 was designed with the less desirable UHF downlinks as the default. If operations permit, the VHF downlink will be used when possible. The digital trasnponder operates at a low transmit duty cycle so it is easy to power relatively high power transmitters. The Amateur Satellite user population only covers 10% of the earths surface and with the low duty cycle of the ALOHA style of APRS operations, less than 4% of PCSAT2's average transmit power budget is required for AX.25.

The VHF link budget on the uplink is also suitable for low power devices and other experiments. There are several student projects using stand-alone tracking devices or data collection buoys or remote WX stations such as the one built by Ronald Ross, KE6JAB in Antarctica [3].

SAT-GATE OPERATIONS

The Mobile-to-mobile and HT-to-HT communication missions work without any special considerations on the satellite or on the ground. But the more useful application of linking these packets to any other APRS station worldwide requires the use of many volunteer ground stations. They feed every packet heard into the APRS-Internet system (APRS-IS). These SAT-Gates perform the following functions:

1) Monitor both downlinks and feed ALL packets into the Internet
2) Maintain a track on all Calls heard via satellite
3) Monitor the Internet and capture MESSAGES for these Calls
4) Deliver these messages repetatively but at a "fair" rate

OMNI NO-TRACK SAT-GATES

Setting up a SATgate is trivial requiring nothing more than a normal packet station and omni antenna. Any APRS station can do it with existing software which contain the built-in Igate capabilities. Even without horizon-to-horizon coverage, each such station simply contributes their packets to the same worldwide stream as all the other Igate receivers. The combination results in over a 99.96% chance of capturing every packet over the USA! Just 4 such stations even if they only have a 60% chance of decoding each packet, combine to a probability of 98%. If the original packet is replicated TWICE, then this probability becomes 99.96%! A Certainty!

CONCLUSION

Modern Technology is on the move. Satellite Wireless is the leading edge of technology and in the Amateur Satellite Service, it should be a major driver for future amateur satellite and educational missions. PCsat has fulfilled this mission objective and now PCSAT2 and ANDE will continue this mission. During the the first 18 months, over 2000 users were logged by the PCsat system feeding the http://pcsat.aprs.org web page and browsers scored over 1000 hits a week from users checking on the status of PCsat or other users.

AX.25 transponders on 145.825 MHz are ideal for extending Amateur Satellite digital communications services to mobile and handheld users because of the availability of not only the off-the-shelf end user mobile and handheld fully integrated data radios but also the off-the-shelf spacecraft design demonstrated by PCsat, PCSAT2 and ANDE.

Combining this with the recent maturity of the Internet as a global resource for exchanging data worldwide suggests that there is a unique opportunity to join the Internet and Amateur Satellites as a means of tying together SatGates throughout the world where the infrastructure exists to extend worldwide amateur communications to mobiles in areas where it doesn't exist.

By encouraging UI digipeating as auxiliary payloads on most small satellites the Amateur Satellite Service can bring all of these pieces together into the most powerful and far reaching Amateur Satellite project to date. Student projects and educational institutions can easily contribute to this capability while also serving their own needs of viable payloads and ongoing operations training.

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